Human Control of Multiple Unmanned Vehicles: Effects of Interface Type on Execution and Task Switching Times

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ABSTRACT
The number and type of unmanned vehicles sought in military operations continues to grow. A critical consideration in designing these systems is identifying interface types or interaction schemes that enhance an operator's ability to supervise multiple unmanned vehicles. Past research has explored how interface types impact overall performance measures (e.g. mission execution time), but has not extensively examined other human performance factors that might influence human-robot interaction. Within a dynamic military environment, it is particularly important to assess how interfaces impact an operator's ability to quickly adapt and alter the unmanned vehicle's tasking. To assess an operator's ability to confront this changing environment, we explored the impact of interface type on task switching. Research has shown performance costs (i.e. increased time response) when individuals switch between different tasks. Results from this study suggest that this task switching effect is also seen when participants controlling multiple unmanned vehicles switch between different strategies. Results also indicate that when utilizing a flexible delegation interface, participants did not incur as large a switch cost effect as they did when using an interface that allowed only the use of fixed automated control of the unmanned vehicles.

Categories and Subject Descriptors
H.1.2 [**Models and Principles**]: User/Machine Systems – *Human factors*.

General Terms
Measurement, Performance, Design, Experimentation, Human Factors.

Keywords
Automation, Delegation, Human-Robot Interaction, Playbook, Unmanned Vehicles, Interruption, Task Switching

1. INTRODUCTION
Many different types of unmanned vehicles (UVs) are being developed for use in aerial, ground, and underwater environments. Next generation UV systems such as the United States Army's Future Combat Systems (FCS) will incorporate numerous ground and air UVs, with the type of UV and team size being reconfigurable components tailored to specific combat missions [3]. In addition, military objectives are focused on allowing a small number of personnel to supervise a large number of UVs. These trends in UV development have created a need for understanding how operator(s) can effectively control a large number of UVs of varying types and capabilities.

If supervisors are going to be responsible for overseeing multiple UVs, it is plausible that they would employ sub-sets of UVs to accomplish different objectives. If a supervisor has to switch between UV(s) performing the same or different objectives, what impact will that have on their performance? Previous research indicates that such task switching, or interruptions, can be disruptive, particularly if there are insufficient environmental cues to allow timely resumption of the interrupted task [2, 15]. In addition to switching between tasks, research has shown that switching between varying levels of automation can result in both positive and negative performance [14]. Therefore, switching between different objectives or between different levels of automation may positively or negatively impact a supervisor's performance.

When managing UV systems a supervisor's ability to effectively react to a changing environment therefore, may be contingent upon the operator having to (1) switch levels of automation, or (2) switch task actions. Level of automation refers to the full or partial replacement of a task (i.e. function) previously carried out by the human supervisor. For example, UV(s) supervised by waypoint-to-waypoint action would represent a lower automation level than a UV supervised by pre-programmed behaviors such as "patrol border". A task action is defined by the strategies necessary to achieve a higher level objective. For example, in the game of capture-the-flag, the highest level objective is to win the game – by capturing the opponent's flag and returning back to own side. To fulfill this objective a player must have both a defensive (protect own flag) and offensive strategy (capture opponent flag).

From these definitions of levels of automation and task action (from here on, referred to as strategy) it is possible to describe situations in which a switch would occur. For example a switch between levels of automation would occur if a supervisor was operating a UV in a waypoint-to-waypoint mode and switched to more automated condition such as "patrol border". A strategy switch would occur if the supervisor went from an offensive strategy to a defensive strategy – or vice-versa. A no-switch

HRI'06, March 2–4, 2006, Salt Lake City, Utah, USA.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Human Control of Multiple Unmanned Vehicles: Effects of Interface Type on Execution and Task Switching Times**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Navy Center for Applied Research in Artificial Intelligence (NCARAI),4555 Overlook Avenue SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
HRI’06, March 2P4, 200a, Salt Lake City, Utah

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

condition would occur if a supervisor contentiously used the same level of automation throughout - e.g. always operated the UV in waypoint-to-waypoint mode. Likewise, if the supervisor continuously used and re-engaged a defensive strategy, then there would be no strategy switch.

The impact of switching between different strategies when utilizing varying levels of automation has not been extensively examined. In particular research has not examined this impact as a function of interface types. Interface type can be described by the interaction possibilities afforded to a supervisor. For example, an interface could constrain an operator's ability to control a UV, by only providing a waypoint-to-waypoint control. Alternatively a more flexible interaction scheme would allow the supervisor the ability to choose between waypoint control and automated control.

The impact of interface type on overall operator performance measures (e.g. mission execution time) has yielded important information about interface design and the potential effect on task switching. Specifically, interfaces that allow operators to task robots flexibly at different levels of automation, or *delegation interfaces* have been found to be especially useful. Delegation interfaces enable the human to set an objective and decide whether to automate (or not) tasks, dynamically during system operations [9]. The Playbook™ is a specific form of a delegation interface that is similar to the sports playbook concept – where there is an approved book of plays, and selections of those plays are performed by the team leader and executed by the team members. To implement Playbook™ the simulation environment RoboFlag (Figure 1) provides the capability to command simulated robots [the rest of the paper will use the term robots rather than simulated robots], individualy or in groups, using either manual control (providing designated endpoints for robot travel) or automated control (higher level behaviors, preprogrammed) such as "patrol border".

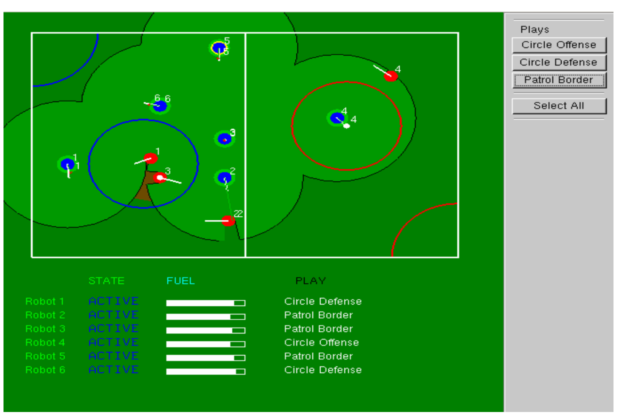

Figure 1. RoboFlag "play" condition interface.

In a series of experiments using Roboflag, Parasuraman, Galster, Squire, Furukawa, and Miller [13] showed that the type of interface available to operators had significant effects on overall human-robot performance. They found that, compared to a restricted interface in which only automated control was available, mission execution times were shorter when the operator was able to flexibly use, at times of their own choosing, either manual (i.e. waypoint) control of robots or automated control (e.g., such as "patrol border"). This benefit was attributed to the operator recognizing conditions where the automation was "brittle" and needed to be over-ridden by tasking the robot(s) in a different way. Benefits of the delegation interface for mission accuracy were also found, and while subjective workload did increase with the use of delegation, the increase was not substantial.

Parasuraman *et al.* [13] used overall mission execution time as a performance metric and did not explore the microstructure of human-robot interaction times as a function of interface type. One possibility is that different interfaces have different effects on the costs of *switching* between strategies. Many basic cognitive psychology studies indicate that when participants have to switch from performing one cognitive operation on a set of stimuli (e.g., addition) to another operation (e.g., addition), that there is an increase in reaction time (RT) following the switch, compared to no-switch conditions [1,8,10,11,12]. The task-switching paradigm has also been used with more complex tasks in which operators have to return to a primary task following interruption by a secondary task [2]. It is reasonable to suppose, therefore, that there will be a switch cost in a multi-robot setting when participants switch between different strategies that they use in supervising the robots. Moreover, if these switch costs are present, how does the type of interface supporting human tasking of the robots affect those switch costs?

One possibility is that switch costs increase more in highly automated interaction schemes between the human operator and the robot, than with lower levels of automation [4]. For example, Crandall, Goodrich, Olsen, and Nielsen [4] estimated higher switch costs for point-to-point (P2P) and multiple-waypoint tasking of robots in a simulated navigation task, compared to less automated interaction involving teleoperation. The basis for this expected performance was derived from the interface efficiency (the increase in performance of a neglected robot from human interaction) of an interaction scheme. Crandall *et al.* [4] indicated that these estimates may not always be accurate, and that further work should be conducted to explore such switch costs. The theoretical importance of these interface efficiency predictions concerns (1) the time necessary to regain awareness of the robot's state, and (2) how different interaction schemes may influence that interaction time.

Interfaces that allow operators to regain awareness of the robot's state more quickly should reduce switch costs, while interfaces that hinder an operator's ability to regain awareness of the robot's state should increase switch costs. Research with delegation interfaces suggests that providing an operator flexibility in making decisions on how to task or maintain awareness of a robot's state should reduce switch costs as well as reducing overall mission execution time.

These proposals suggest that it would be worthwhile to re-examine the effects of delegation interfaces on human-robot teaming performance taking switching costs into account. Accordingly, we conducted a study on the effects of delegation interfaces on human-robot interaction using the RoboFlag simulation. We hypothesized that different interface types would result in different switch costs. Second, following Crandall *et al.* [4], we also reasoned that lower levels of automated control of robots, such as waypoint-to-waypoint control, would incur lower switch costs than when participants used automated plays. In addition, based on our previous results [13], we hypothesized that a flexible delegation interface would also reduce switch costs

compared to restricted interfaces in which the operator only had the option of using automated control.

2. METHODS

2.1 Participants

Twelve adults, 7 males and 5 females aged 18 - 22 years (M = 20.1 yrs., SE = 0.4 years.) served as paid participants. All participants reported normal or corrected to normal visual acuity.

2.2 Experimental Design

A within-subjects design was employed using interface conditions selected from the different combinations of automation level (or abstraction) and robot selection (or aggregation) – see Figure 2. Automation level was defined as a continuum of tasking action as applied to individual or groups of robots. At a low level, the supervisor could use waypoint-to-waypoint movement control of the robot (an even lower level would involve telerobotic control, but in this study only robots capable of autonomous movement were considered). Waypoint movements (i.e. manual control) were defined as the selection of some number of robots followed by pointing and clicking to a desired location in the field to which the robots would move. At a higher task level, the operator tasked single or multiple robots with "plays". Plays consisted of pre-planned continuous movement actions and reactions to events (e.g. a participant's robot takes action to not be tagged by an opponent robot). At the highest task level, the operator had the option to use "superplays," which consisted of a mix of different plays using more than one robot. The second dimension, robot selection, was defined as the number of robots to which particular tasks were assigned. "Individual" robot selection referred to commands given to an individual robot. "All" robot selection meant tasking all robots with the same action (i.e. waypoint, play, superplay). "Group" robot selection was also possible where tasks could be given to groups of robots smaller or equal to that of the whole team.

Figure 2 depicts the experimental conditions and the two dimensions of the delegation interface, robot selection (on the X axis) and automation level (on the Y axis). A specific X,Y coordinate represents an interface condition that is either restricted or flexible along those two dimensions. A restricted interface is constrained (i.e. non-selectable) to a specific level along each dimension. A flexible interface is either not constrained or is constrained on only one dimension.

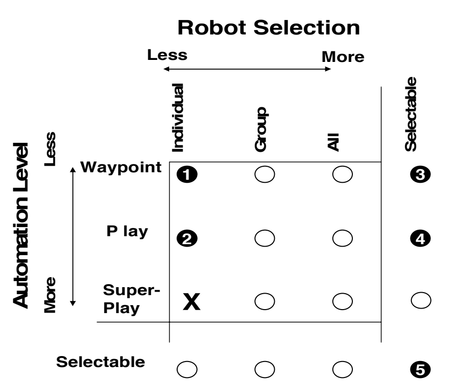

Figure 2. Interface combinations (conditions 1-5)

For example, the combination of "Individual-Waypoint", identified as Coordinate 1 in Figure 2, represents a restricted interface condition – Figure 3 shows the interface presentation for an operator. In this condition participants are required to supervise individual robots using only waypoint movements; no other options are available.

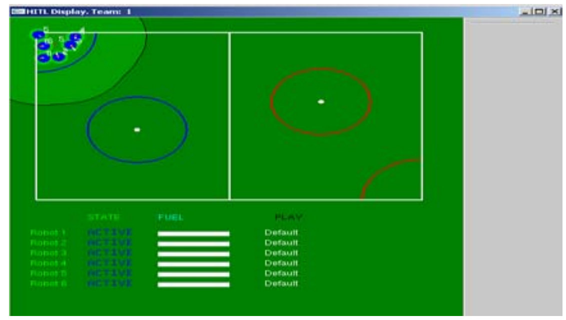

Figure 3. Individual Waypoint Interface Condition

The combination of "Selectable-Play", identified as Coordinate 4 in Figure 2, represents a flexible interface condition – Figure 4 shows the interface presentation for an operator. In this condition participants can flexibly choose how to select robots, whether an individual, group, or all; however, the flexibility is limited because they are constrained to using only plays.

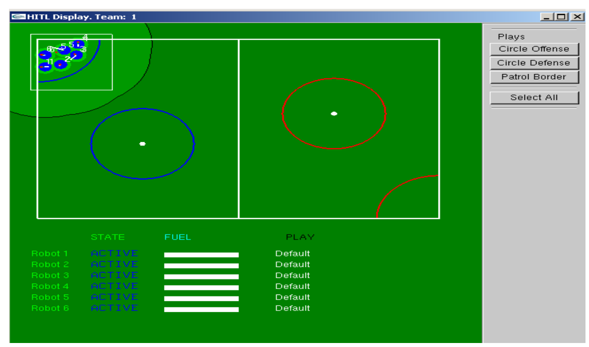

Figure 4. Selectable Play Interface Condition

As shown in Figure 2, five different interface conditions were selected: (1) individual waypoint, (2) individual play, (3) selectable waypoint, (4) selectable play, and (5) selectable selectable. Conditions 1-2 were selected as representative examples for restricted interfaces. Conditions 3-5 were selected representative flexible interfaces with condition 5, representing the optimal (i.e. most flexible) delegation interface.

These conditions were combined factorially with the number of robots controlled by the participant (four, six, or eight robots). Interface condition was treated as a blocked factor while the number of robots controlled was randomized within each block. Each participant completed two sessions (sessions were conducted on the same day), one session consisting of three blocks, and the other two blocks. Session and condition were counterbalanced to offset order effects. A single block had a total of 15 trials (five trials with 4 robots, five with 6 robots, and five with 8 robots) for a total of 75 trials. Participants completed mental workload and situation awareness ratings (0 (low) to 100 (high)) after each trial, similar to the NASA-TLX [5] and the 3-D SART [14] subjective

measure questionnaires. Robotic usage measures and performance data were also logged for each trial.

Two strategy actions, *offensive* or *defensive,* were defined. During waypoint (i.e. point-to-point clicking) interface conditions, an offensive or defensive task was defined by the end-point (i.e. where the robot was directed to move) location. If the robot location at which the action was implemented (i.e. x and y coordinates) was on the offensive side or opponent area (as seen in Figure 1, the mid-line distinguished the participant's area (left) and opponent's area (right)), then the action was defined as an offensive task. If the location was on the defensive side of the playing field then it was categorized as a defensive task. During interface conditions in which participants could use plays, an offensive task was defined as the selection of an offensive play (e.g. circle offense). A defensive task was defined as the selection of a defensive play (e.g. circle defense).

A strategy switch occurred when the participant switched from an offensive to a defensive strategy or from a defensive to an offensive task. In contrast, a task was considered a no-switch task when the same task was repeated (e.g. offensive, offensive, offensive). For each trial, grand averages were computed for switch and no-switch tasks by summing the times taken for each task action and dividing by the number of actions for each. Since the first task action performed during each trial did not have a previous task action to which it would be referenced those times were not included in the computations (see Table 1 for example computations, and Figure 5 for illustration).

Table 1. Computation of mean switch and no-switch times

Action(Action Type)	Total Time	Switch Time	No-Switch Time
Defensive (First Action)	2.17	-	-
Defensive (No-Switch)	3.83	-	1.66
Defensive (No-Switch)	4.5	-	0.67
Offensive (Switch)	6	1.5	-
Offensive (No-Switch)	6.57	-	0.57
Defensive (Switch)	9.7	3.13	-

Type (NS = No-Switch Time, S = Switch Time)

Strategy (D = Defense, O = Offense)

Type	N/A	NS	NS	S	NS	S
Strategy	D	D	D	O	O	D
Time (s)	2.17	1.66	0.67	**1.5**	0.57	**3.13**

Figure 5. Illustration of Strategy Usage as defined by Switch and No-Switch Actions

Apparatus and Procedures

The RoboFlag simulation ran on two separate PCs communicating under TCP/IP protocol. The participant used one PC while another PC ran the opposing team script, and recorded log files. To observe participants' actions unobtrusively, an additional monitor was used by the experimenter for observation. The basic RoboFlag objectives and architecture were unchanged from previous studies [13], but changes made to the RoboFlag environment are described below. Of the five experimental conditions selected, two represented restricted interfaces (individual waypoint, individual play), and three flexible interfaces (selectable waypoint, selectable play, and selectable selectable). The opponent force consisted of 6 robots that were scripted to have a mixed "posture", defending their flag half the time and going on offense during the remaining half. When the opponent team conducted offensive maneuvers, the attacking routes of the robots were varied in an unpredictable manner.

Participants received instruction (but with no specific strategy guidance) on interface features and procedures for robot selection and movement. Three training trials were conducted for each condition for each robot number (4, 6, and 8). During experimental trials, participants were told the number of robots before each trial. A trial concluded when either the participant or opponent had captured the flag and crossed the mid-line to their side.

3. RESULTS

Given the limited space for this paper, results are reported only for: (1) overall mission execution time, (2) Fitt's law movement calculations, (3) number of strategies used during a trial, and (4) switch / no-switch results. Mission execution time data were submitted to an ANOVA and resulted in a main effect for Interface condition, $F(4,44) = 4.29$, $p < .01$. A planned comparison between the manual only (individual waypoint and selectable waypoint) and automated only conditions (individual play and selectable play) revealed a significant effect $t(11)$, = -4.60, $p < .001$, with mission execution time significantly longer for the automated only condition, than the manual only condition (see Figure 6). This result illustrates the same general effect obtained by Parasuraman *et al.* [13]. When participants were restricted to the use of automated plays only, overall human-robot performance was less efficient. Moreover, when operators could flexibly use either waypoint control or automated plays (selectable all), mission time was reduced, although in this study this was only a marginally significant effect.

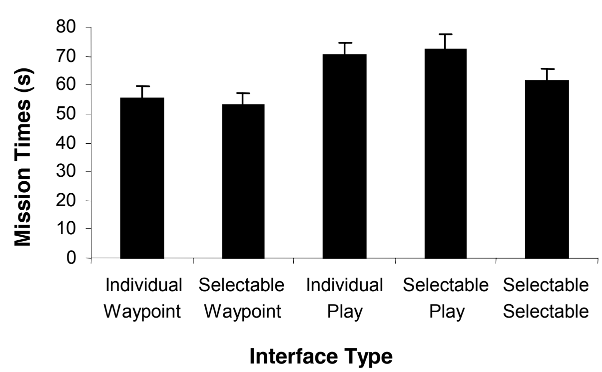

Figure 6. Mission Time for Interface Conditions

We also analyzed the time it took operators to switch from one type of strategy to the other (e.g., offensive to defensive), and compared these to cases where participants implemented strategy actions that did not switch (e.g., offensive to offensive). Because the physical action for implementing a strategy was a mouse click, the motor movement time in moving the cursor needed to be assessed before switch and no-switch times could be analyzed. Fitts' Law was used to calculate movement time – in this case the time required to move the cursor from one position on the graphical user interface (GUI) to another position. The specific version of Fitts' Law known as Shannon's formulation was used – $MT = a + b \log2(2A/W + 1)$, where MT is the movement time, a,b are the regression coefficients for a particular user and mouse, A is the distance of the movement from start to target center, and W is the width of the target. The regression coefficients used for point and click mouse moves were taken from Mackenzie's, POINT-SELECT [7]. The GUI movement times for the best and worst case are provided in Table 2. The best case GUI movement time represented a situation where the participant made a very small motor movement, such as when the operator changed a play without having to de-select the robot. For example, if the operator switched from a circle offense play (top most play in Figure 1) to a circle defense play then the operator only needed to move 0.80 inches on the GUI. If however, the operator selected a robot at the left most bottom corner of the playing field, and then selected circle offense, the action required a motor movement of 6.4 inches. This represented a worst case situation.

Table 2. Best and Worst Case Movement Time Predictions

Fitts' Law Calculations	Total (seconds)	A value (inches)	W value (inches)
Best	0.43	0.80	0.63
Worst	0.81	6.40	0.63

This analysis indicates that the average movement time to execute a strategy change was relatively short (~ 0.6 s on average). As shown later, the computed switch times were considerably longer (from 2 to 7 s) than the mean motor movement time. Therefore the contribution of changes in motor movement time to changes in switch time with changes in the interface are likely to have been small.

We next analyzed changes in the number of strategy actions for the different interface conditions and number of robots. The absolute counts for number of actions performed were submitted to a 2 X 5 X 3 analysis of variance (ANOVA) with factors of strategy switch type (switch, no-switch), interface condition (individual waypoint, individual play, selectable waypoint, selectable play, and selectable selectable), and number of robots (4,6,8). There was a significant main effect for strategy type, $F(1,11) = 24.32$, $p < 0.01$. Indicating that significantly more no-switch strategy actions (M = 21.57, SE = 3.58) than switch strategy actions (M = 3.58, SE = 0.28) were performed. There was also a significant main effect of interface condition on actions performed, $F(4,44) = 5.35$, $p < 0.05$. As illustrated in Figure 7 most of the variation between the number of actions performed seems to be due to the no-switch rather than the switch strategy actions.

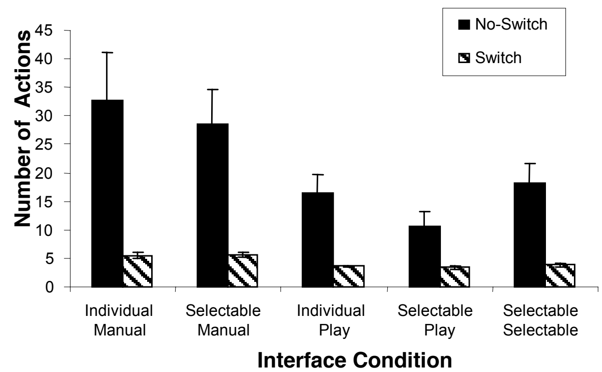

Figure 7. Number of Actions for continuous and switch tasks by Interface Conditions.

The only other significant effect obtained was for the number of robots, $F(2,22) = 3.90$, $p < 0.05$. Post hoc pairwise comparisons with a Bonferroni adjustment gave a significant effect for robot number, $p < 0.05$; participants performed more actions with 8 robots (M = 13.90 actions, SE = 2.13) than with 4 robots (M = 11.67, SE = 1.93) [see Figure 8].

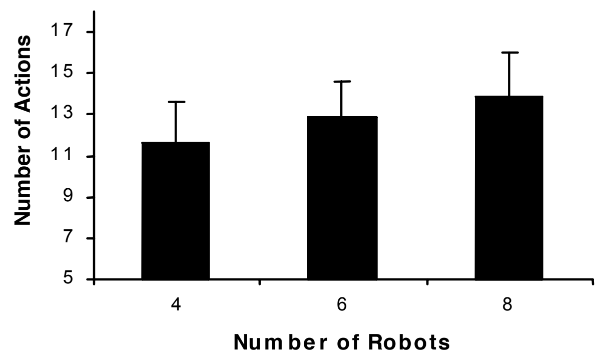

Figure 8. Number of Actions for Number of Robots.

To assess the changes in switch and no-switch times with interface type and robot number, a 2 X 5 X 3 ANOVA was computed with the same factors as before. Significant main effects were obtained for task type, $F(1,11) = 78.50$, $p < 0.01$ and interface condition, $F(4,44) = 20.13$, $p < 0.01$. The only other significant effect was the interaction between strategy type and interface condition, $F(4,44) = 10.88$, $p < 0.01$ [see Figure 9]. As expected, participant's times were longer for switch strategies (M = 4.59 s, SE = 0.29 s) than for no-switch strategies (M = 1.87 s, SE = 0.18 s).

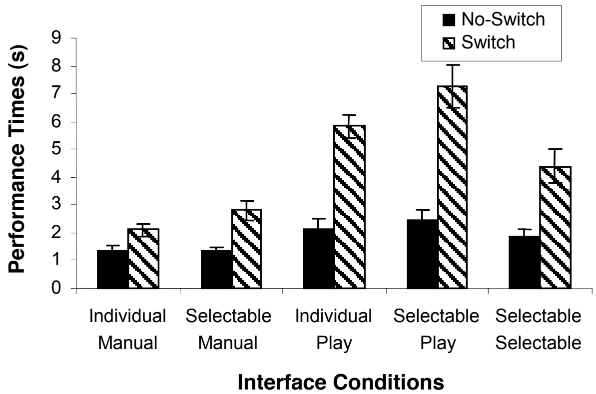

Figure 9. Switch and No-Switch times for Interface Conditions.

To examine the hypothesis that switch cost effects were lower for manual than automated conditions, pairwise comparisons were conducted between the manual, automated, and selectable selectable. As expected there were no significant differences obtained for no-switch strategies ($p > 0.02$, $\alpha = 0.05/3$), and three significant differences for switch strategies. The manual switch task (M = 2.47 s, SE = 0.26 s) was faster than the automated switch task (M = 6.55 s, SE = 0.44 s), and selectable selectable switch task (M = 4.40 s, SE = 0.62 s), $t(11) = 8.50$, $p < 0.01$ and $t(11) = 3.16$, $p < 0.01$ respectively. In addition the selectable selectable switch task action, while slower than the manual switch task, was significantly faster than the automated switch task, $t(11) = 3.45$, $p < 0.01$ [see Figure 10]. These findings indicate actions or tasks that are more specific in nature (e.g. waypoint action) are less complex and therefore reduce the switch cost times associated with those tasks. However, automated tasks appear to add additional complexity (e.g. an operator has to consider the impact of an automated play with multiple tasks associated with it) that results in increased switch cost times.

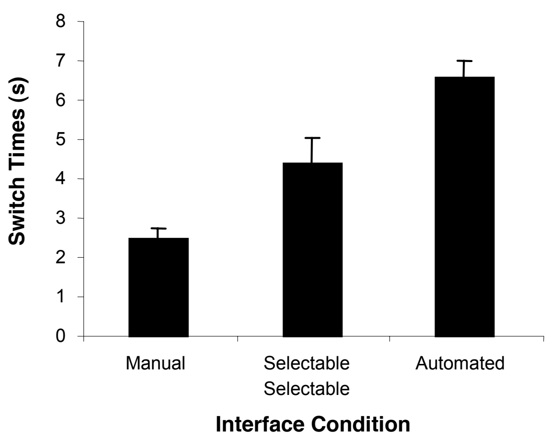

Figure 10. Switch times for Manual, Selectable Selectable, and Automated Interface Conditions.

4. DISCUSSION

The present study of multi-robot control using the RoboFlag simulation examined the effects of interface type and number of robots controlled on overall mission execution time as well as task switching times. Consistent with our previous findings [13], restricting participants to the use of an interface that allowed only automated plays was associated with longer mission completion times. At the same time, there was a trend for reduced mission completion times when participants could flexibly use either waypoint control or automated plays, providing general support for the efficacy of delegation interfaces.

We also examined switch times for instances when participants implemented a different tasking action, e.g., from offense to defense, on a robot or group of robots. The results showed that such switch times were relatively long, on the order of 2-7 s. These delays represent a significant switch *cost*, because switch times were significantly longer than no-switch times (1-2 s), when participants initiated successive robot tasking actions that were the same (e.g., both offensive), and substantially longer than the mean motor movement time required to execute the action using a mouse click (~ 0.5 s). These values for switch costs are comparable to those reported in previous studies with complex multi-task [2] and robot simulations [6].

The results supported the general hypothesis that switch costs would vary with interface type. The range of variation was considerable (2-7 s), indicating that interface type could be a major limiting factor in human supervision of multiple robots, particularly in high-tempo operations. Given the goal of many programs of having a single operator supervise as many robots as possible, these findings indicate that single operator control of many robots may not be feasible for certain interface types. Second, it was hypothesized that switch costs would be greater when participants had to use automated plays than for interaction at a lower of automation, as in waypoint-to-waypoint control. The results supported this prediction as well. Whereas mean switch time for the individual manual condition was about 2 s, switch time for the individual play condition was about 6 s, a three-fold increase. The increase in switch time for more automated levels of interaction with multiple robots is also consistent with the findings of Crandall *et al* [4], who compared teleoperated, waypoint-to-waypoint, and multiple-waypoint methods of robot interaction in a simulated navigation task.

In addition, we hypothesized that a flexible delegation interface, where participants could choose between different task levels, would reduce switch costs compared to restricted interfaces. This prediction was partially supported. In our previous study [13], we found that when participants were provided the ability to delegate (or not) task functions to automation, they benefited from being able to use manual control flexibly with automation to reduce their overall mission execution time. Likewise, when participants in the present study were provided the ability to delegate, they received a similar benefit in the form of a reduced switch cost, from 6 s (in the individual play condition) to about 4 s (in the selectable selectable condition).

The task switching measure used in the present study, following the procedure developed by [2] provides a framework for exploring timing differences associated with the use of different interfaces for controlling multiple UVs. The metric provided useful information on the relative merits of different delegation interfaces beyond that gained from analysis of overall mission completion time. Future research should seek to investigate more specifically the characteristics of task switching in human-robot

interaction, and to examine how task switch costs impact global measures such as mission execution time or mission success.

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